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AUTHOR(S):

Mikumo, Takeshi

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50. A Study on Crustal Structure in Japan by the Use of Seismic and Gravity Data.

By Takeshi Mikumo,*

Disaster Prevention Research Institute, Kyoto University.

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Abstract

Crustal structure in some regions of Japan has been discussed on the basis of the results of refraction measurements, correlation between computed and Bouguer gravity anomalies and between theoretical and observed phase velocities of Rayleigh waves.

The already-derived single-layer crustal models do not seem to be consistent with observed gravity and surface wave data. Alternative structures with double layered or three-layer crust are presented for all the regions by the re-interpretation of travel time data. Comparison of theoretically-predicted values with the observations favors a three-layer solution for western and central Japan, suggesting the existence of a lower crustal layer and a thick intermediate layer over the mantle. A high Poisson's ratio would occur in the intermediate and the upper mantle under central Japan including the Chubu mountain region. In eastern Japan, it is not certain whether there is a thin intermediate layer or not, but the average crustal density might be slightly smaller than that in other regions.

The depths to the base of the lower crust are estimated to be 32–35 km in the Tohoku, 27–31 km in the southeast Kwanto, 38–40 km in the northwest Kwanto, 36–40 km in the Chubu, 28–30 km in the Kinki, and 25–28 km in the Chugoku regions respectively.

The average crustal structures in Japan and North America are compared.

1. Introduction

Much work has been done on the crustal structure in Japan, on the basis of seismic refraction measurements, observation of surface wave dispersion, and of the analysis of gravity anomalies. It is not always to

* Communicated by Prof. S. Miyamura.

be expected, however, that any exploration technique will lead to a unique solution of the problem. It may be reasonable to consider that a combined use of all available information provides the possibility of extracting some reliable conclusions from many possible solutions. Actually, some investigators have made such an attempt in their crustal studies, with the basis on the Bouguer gravity anomalies (Kanamori, 1963), or the phase velocity of Rayleigh waves (Aki, 1961, Kaminuma and Aki, 1963). Another approach would be a combined analysis of seismic and gravity data based on the results of refraction studies, which could offer direct information on crustal layering under favorable circumstances.

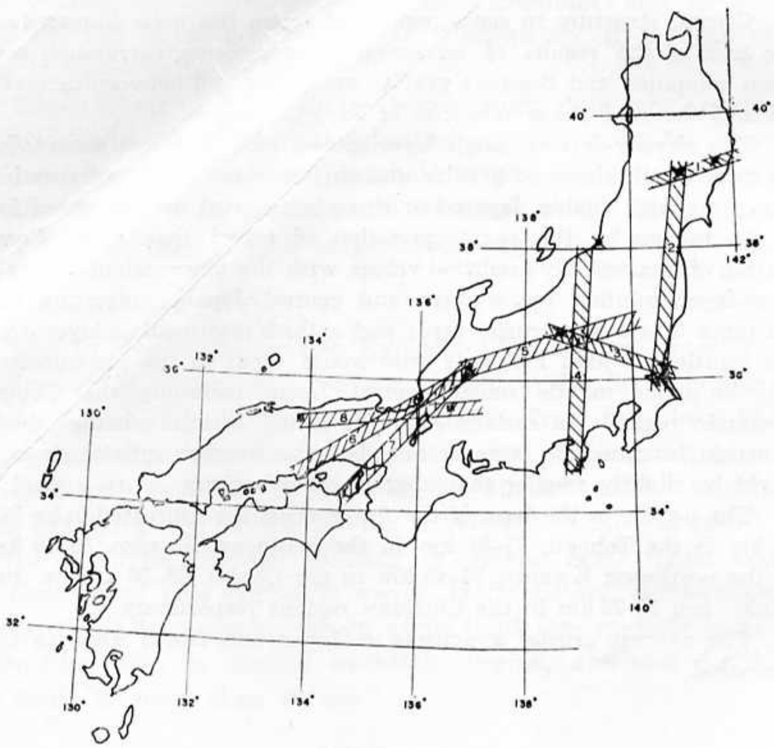


Fig. 1. Seismic profiles mentioned in the present study.

The Research Group for Explosion Seismology has made extensive seismic refraction observations since 1950 (R.G.E.S., 1951–1966) along some profiles over Japan (Fig. 1), and presented probable models of the crustal structures. In early years of explosion seismology, a single-layer model of the crust had been adopted up to 1961. It may be that the evidence of intemediate layers was not clearly identified or has been missed because of widely spaced recording sites. Kanamori (1963) pointed out that the derived models with a single-layer crust do not seem to be supported by other evidences, suggesting the possible existence of a masked layer and an intermediate layer in and under the crust. Later observations made along the 139°E line (R.G.E.S., 1964), on the other hand, have revealed the existence of a lower crustal layer with a compressional velocity of 6.8 km/sec. In recent refraction measurements of the Kurayoshi-Hanabusa explosions, an apparent velocity higher than 8.0 km/sec for Pn waves and velocities indicating intermediate layers have been observed. For both profiles, crustal models with two or three layers, which are quite different from those proposed for the other regions, have been presented. It should be noted, however, that the crustal models have been derived exclusively from their observations, without much quantitative considerations to gravity and surface wave data, in the course of the analysis.

Our aim in this paper is to infer the general features of crustal structure in some regions of Japan, from travel time data in the refraction studies, comparison between computed and observed gravity anomalies and between theoretical and observed phase velocities of surface waves. As a first step to this study, two dimensional distributions of gravity anomalies are computed from some of the crustal models that were presented by the R.G.E.S., and are compared with the corresponding sections of Bouguer anomalies. The next step is a re-interpretation of all travel time data already obtained in 7 profiles, and some possible models are presented as alternatives, on the assumption that there may be lower crustal or intermediate layers underlying the upper crust. The gravity anomalies expected from all the models are again computed in comparison with Bouguer anomalies, and theoretical dispersion curves of the phase velocity of Rayleigh waves are also computed from the presented models to compare with the observation. The probable structures in the western, central and eastern regions are discussed, using the combined results of the three kinds of information.

2. Computation of Two-dimensional Gravity Anomalies and Related Problems

To compute the gravity anomaly distribution from a seismic structure, it is necessary to know a velocity-density relation and a standard crustal section to be referred, including a depth of compensation. It is also important for a comparison between the observed and computed anomalies to estimate variations due to the change in related parameters.

(1) Method

In the present study, we use the method developed by Talwani and others (1959), to compute the gravitational attraction due to crustal layers with two-dimensional configurations, parameters of which have been determined from seismic measurements. The vertical component V of the attraction from the whole of m layers is expressed in the following form (Mikumo, 1965):

$$V=2G\sum_{j=1}^{m}\rho_j\sum_{k=1}^{n_j}(x_{j,k+1}\Delta z_{j,k}-z_{j,k+1}\Delta x_{j,k})(-\Delta\theta_{j,k}\Delta x_{j,k}+\Delta z_{j,k}\log_e(r_{j,k+1}/r_{j,k}))/\Delta r_{j,k}^2$$

$$\Delta x_{j,k}=x_{j,k+1}-x_{j,k},\ \Delta z_{j,k}=z_{j,k+1}-z_{j,k},\ \Delta\theta_{j,k}=\theta_{j,k+1}-\theta_{j,k},\ \theta_{j,k}=\tan^{-1}(z_{j,k}/x_{j,k}),$$

$$r_{j,k}^2=x_{j,k}^2+z_{j,k}^2,\ \Delta r_{j,k}^2=\Delta x_{j,k}^2+\Delta z_{j,k}^2$$

where $(x_{j,k},\ z_{j,k})$ are the coordinates of the k-th edge in the j-th layer which is approximated by a n_j-sided polygon, ρ_j is the density of the layer, and G the universal gravitational constant.

(2) Standard structure

If a standard structure is composed of the crust and mantle with the mean densities of ρ_C and ρ_M respectively and a crustal thickness of H_S, the theoretical anomaly should be given as follows, subtracting the attraction V_0 caused by the adopted standard section for which the anomaly is zero,

$$\Delta g=-2G\sum_{j=1}^{m}(\rho_m-\rho_j)\sum_{k=1}^{n_j}f(x_{j,k},\ z_{j,k})+2\pi G(\rho_M-\rho_C)H_s+2\pi G(\rho_m-\rho_M)\overline{H},$$

ρ_m being the density of the m-th layer (or the upper mantle) in the model considered. The last term comes from a density difference in the upper mantle between the present model and the reference structure, and the difference is assumed to vanish under a depth of $\overline{H}$. $\overline{H}$ means the depth of compensation below which material does not substantially contribute to the anomaly. As a standard section we may refer to, for example, the standard continent of Worzel and Shubert (1955), but in Section 3, $\rho_M=3.18\,g/cm^3$, $\rho_C=2.75\,g/cm^3$, $H_S=33$ km and $\overline{H}=36$ km are tentatively given, keeping the density contrast and crustal thickness the same as in the continent. There could be appreciable difference, however, in the absolute anomaly values due to the choice of a reference. In Section 4, a standard crust is not assumed beforehand but will be determined in such a way that a best fit over all profiles may be found between the computed and Bouguer anomalies.

(3) Velocity-density relation

Densities to be assigned for the crustal layers may be evaluated from empirical relations between compressional velocity and density, although a unique relation cannot be defined in view of the appreciably scattered data. Fig. 2 shows the smoothed curves given by Woollard (1959) and Nafe and Drake (Talwani *et al.*, 1961) for field data and by Birch (1961) from laboratory experiments under a high pressure, together with a mean curve (M) for the above three. The last is mainly used in later computations, comparing the results with those from the other three relations.

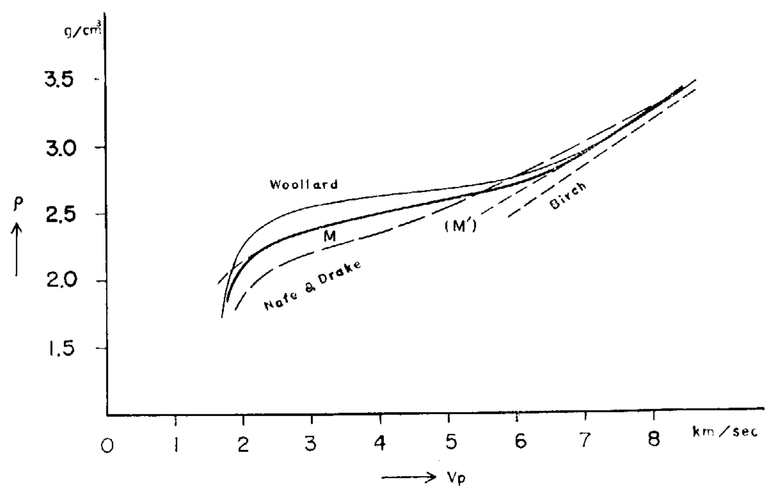


Fig. 2. Compressional velocity-density relations.

(4) Estimation of errors in the two-dimensional calculation

1) There may be a question whether the two-dimensional computa-

tion could be applied to our profiles in Japan where the structure varies rather abruptly from place to place. In order to estimate errors in the present case, we shall consider such simple cases as shown in Fig. 3, in which the structure changes uniformly in the direction perpendicular to the profile considered. V is the attraction at O due to these models, and V_∞ is that from a body with a constant thickness of z_2-z_1 which is assumed in the case of two-dimensional calculations. If z_1/z_2 is taken to be 0.3, V/V_∞ does not drop down to 95% for z_2/d less than 0.1 in the case of (a), while it is 82% in (b). The case of $z_2/d=0.1$ corresponds to a gravity anomaly gradient of 1.3 mgal/km taking a density contrast as 0.43. It may be said that the errors resulted from the two-dimensional calculation are within 5% where observed gravity anomalies vary uniformly with a rate less than 1.3 mgal/km in the direction perpendicular to the profile concerned. At most of the points on our profiles the above condition is satisfied.

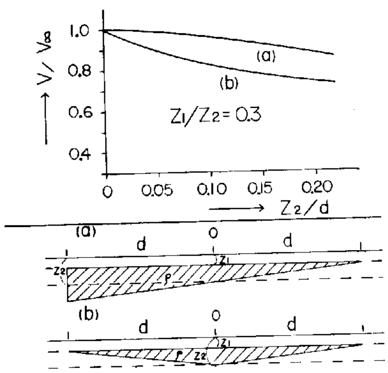


Fig. 3.

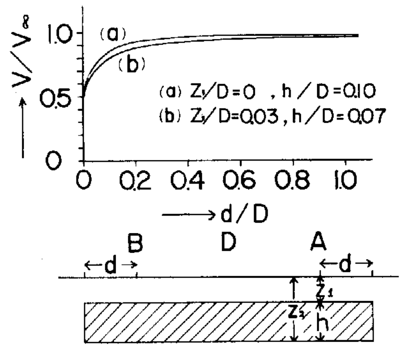


Fig. 4.

2) It is also important in the gravity computation to estimate the end effect of a profile. Suppose a simplified mass distribution shown in Fig. 4, D being the length of a profile over which gravity values are to be calculated. V and V_∞ are the attractions at the point A (or B) due to the truncated and endless bodies having a constant thickness of h. It can be seen that the truncation effect is about 5% for $d/D=0.5$ and should be reduced to less than 3% if we extend the same length of the profile to both sides. In later computations the structure outside in the latter range is taken into account.

(5) Effect of sedimentary layers

Surface geology has not been well surveyed yet over our seismic profiles except near shot points in explosion observations. Only sedimentary layers derived from the observations are taken into the gravity computations. The possible existence of sedimentary deposits with unknown low densities and depths could introduce considerable effects into computed gravity values.

(6) Bouguer anomalies

The computed gravity anomalies are compared with the distribution of Bouguer anomalies, which were taken by interpolation along seismic profiles mainly from the Bouguer gravity maps compiled by the Geographical Survey Institute (1957, 1964) and partly from those by Tsuboi and others (1953–1956). It would be necessary before a direct comparison to evaluate the possible variation of Bouguer anomalies in making various reductions. i) There is some difference between the standard gravity at the latitudes of Japan and the International standard gravity usually used in the reduction. (Tsuboi, 1933). ii) There is also a difference between the customarily used Bouguer anomaly at various elevations and the real Bouguer anomaly at sea level, depending on the vertical gradient of gravity (Fujii, 1964; Tsuboi, 1964). iii) A density of 2.67 g/cm^3 used in the Bouguer correction is not always the same value over the area considered. iv) Interpolations along a profile from a Bouguer gravity map could introduce larger errors. v) Seismic recording stations do not lie on a line but in a belt-like area with a width of 20–30 km. In the figures in later sections are shown the range of Bouguer anomalies within the area.

It may be concluded from the foregoing estimations through (2)-(5) that discussions on a discrepancy less than 50 mgals between computed and Bouguer anomalies would probably be insignificant. For this reason, our discussion will be focused on a comparison between relative anomalies or the general trend of the anomalies over a profille and between the mean anomalies in various regions.

3. Gravity Anomalies from Seismic Structures derived by the R.G.E.S.

The gravity anomaly distribution along 8 profiles shown in Fig. 1 has been computed here on an IBM 7090 computer by the technique described above from seismic crustal models that were derived by the R.G.E.S.. Figs. 5-12 show the computed (solid and dotted lines) and Bouguer anomaly distribution (short vertical lines bounded by two broken curves), together with the presented models (Matuzawa, 1959; Matuzawa *et al.*, 1959; Usami *et al.*, 1958; Hotta *et al.*, 1964; Mikumo *et al.*, 1961; Hashizume *et al.*, 1966). Densities assigned are shown in brackets in the figures.

(1) Tohoku (Fig. 5) Although there is some discrepancy between the computed and Bouguer anomalies toward the west of the profile, this may be that the lower structure has not been well determined. No further discussion will be made until more detailed information can be obtained from recent seismic observations of the Kesennuma explosions made by the R.G.E.S..

(2) Kwanto-Tohoku (Fig. 6) The distribution of the computed anomalies turns out to be an increase toward the Tohoku region along this profile, while the Bouguer anomalies decrease there. The rather serious discrepancy between the general trends cannot de explained by the allowance for some factors mentioned in the last section.

(3) Kwanto (Fig. 7) There is also disagreement between the computed and observed anomalies particularly in the northwest region, which could not be reconciled by the modification of a velocity-density relation.

(4) Chubu N-S (Fig. 8) The computed anomalies from Model I agree fairy well with Bouguer anomalies. This seems to support the existence of a lower crustal layer with a velocity of 6.8 km/sec in this region, and favors the interpretation that the velocity just beneath the Moho-discontinuity may be closer to 7.9 than to 8.1 km/sec. There is another possibility, however, that an intermediate layer could exist between the lower crust and the upper mantle.

(5) Chubu-Kwanto (Fig. 9) The computed anomalies from the two presented models are not consistent with the Bouguer trend. The main reason may be that the structure has not been reversed yet.

(6) Kinki A (Fig. 10) A remarkable reverse trend of the computed anomalies from Model I against the Bouguer distribution does not give support to this model, while those from Model II run parallel with comparatively large gaps.

(7) Kinki B (Fig. 11) The models are based on the Miboro explosions. Appreciable disagreement between the two kinds of anomalies is seen towards the northeast and southwest directions in Model I and over the profile in Model II.

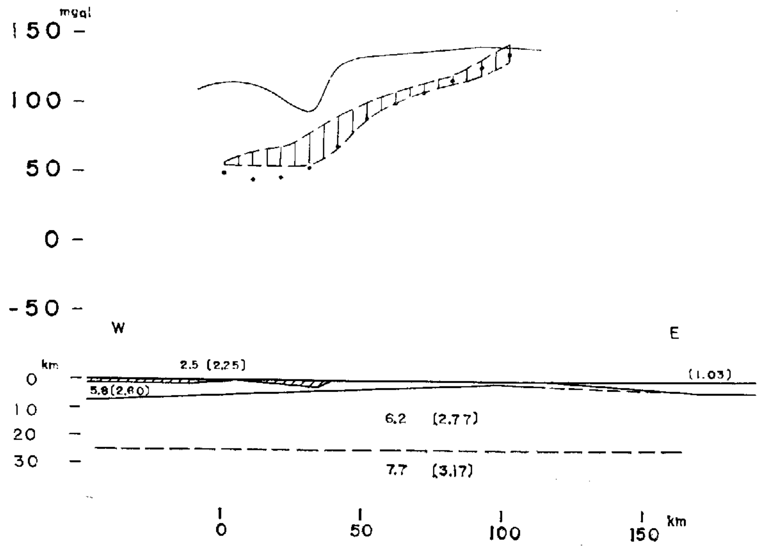


Fig. 5. Computed and Bouguer gravity anomalies, and the presented crustal model (after Matuzawa) along the Tohoku profile.

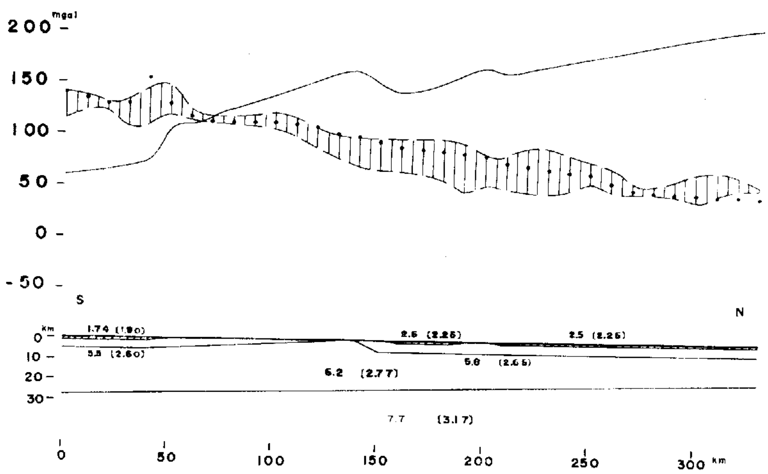


Fig. 6. Computed and Bouguer gravity anomalies, and the presented crustal model (after Matuzawa *et al.*) along the Kwanto-Tohoku profile.

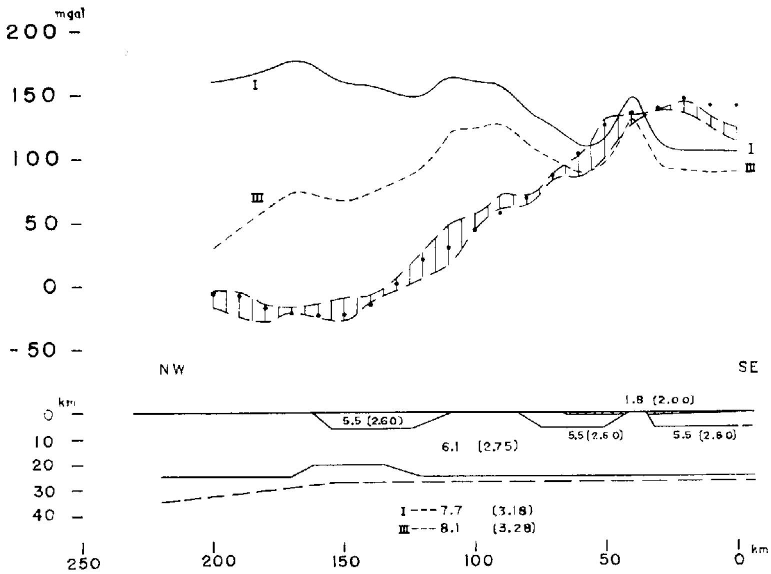


Fig. 7. Computed and Bouguer gravity anomalies, and the presented crustal model (after Usami *et al.*) along the Kwanto profile.

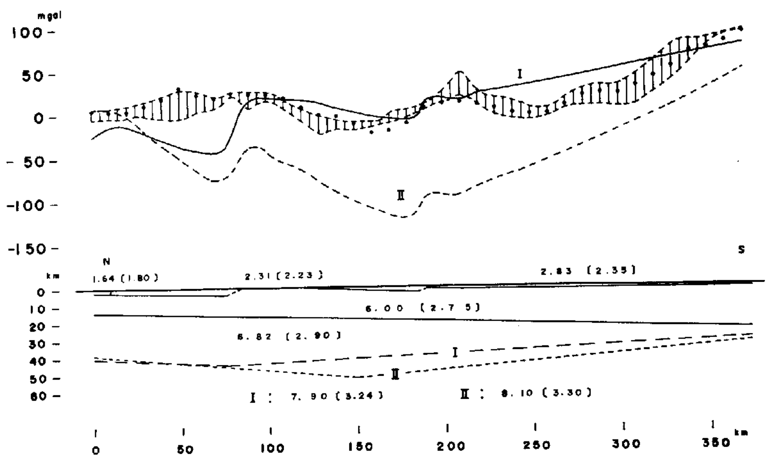


Fig. 8. Computed and Bouguer gravity anomalies, and the presented crustal model (after Hotta *et al.*) along the Chubu N-S profile.

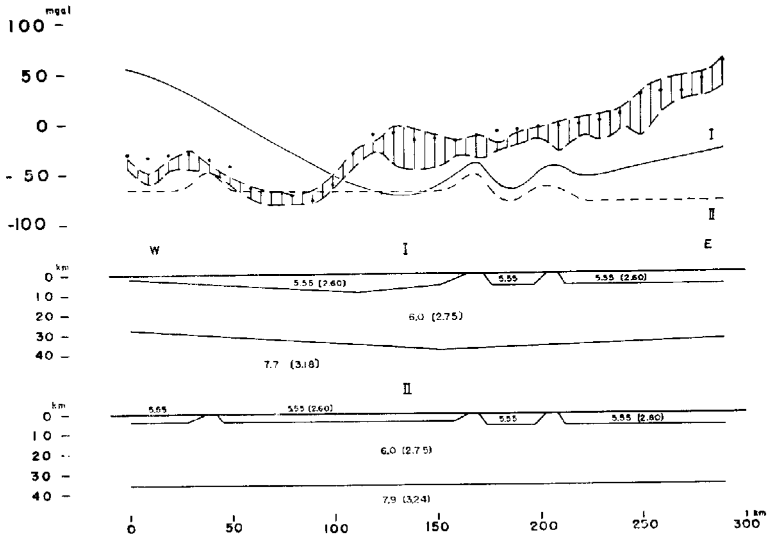


Fig. 9. Computed and Bouguer gravity anomalies, and the presented crustal model (after Mikumo *et al.*) along the Chubu-Kwanto profile.

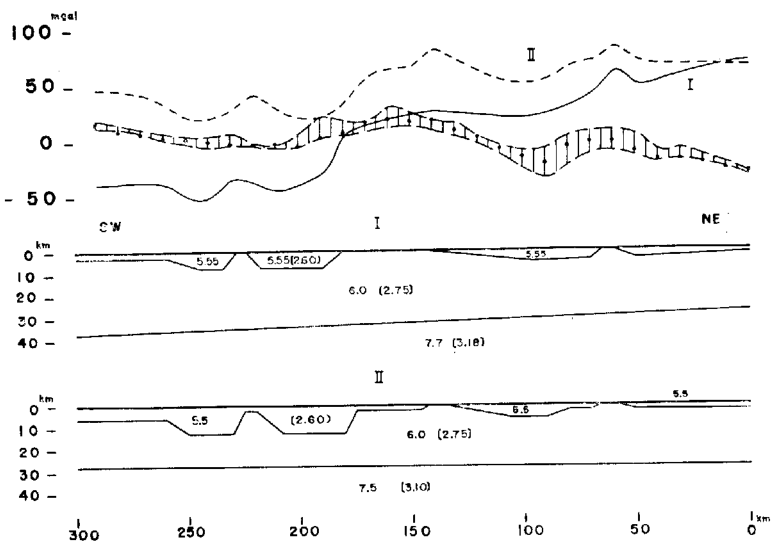


Fig. 10. Computed and Bouguer gravity anomalies, and the presented crustal model (after Mikumo *et al.*) along the Kinki A profile.

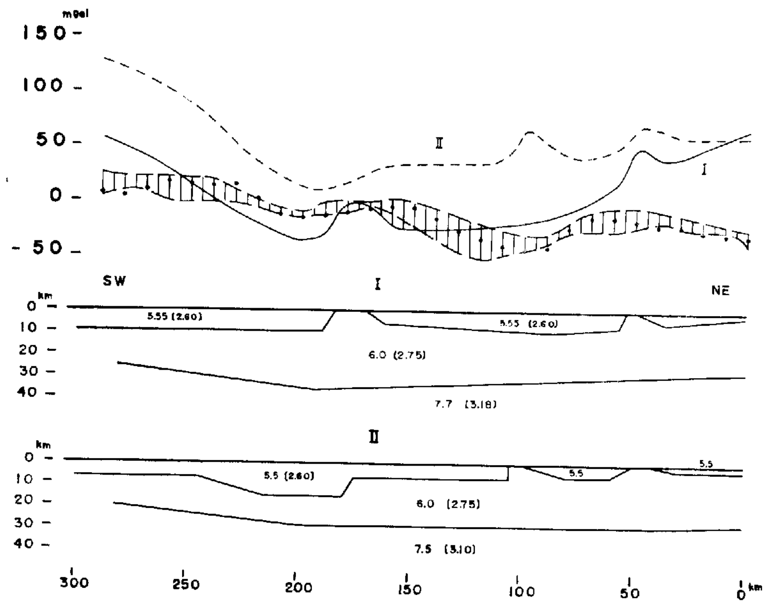


Fig. 11. Computed and Bouguer gravity anomalies, and the presented crustal model (after Mikumo *et al.*) along Kinki B profile.

(8) Chubu-Kinki-Chugoku (Fig. 12) Two probable models have been presented by the R.G.E.S., based on the results frcm the Kurayoshi-Hanabusa explosions. Limits of the allowance for the depths of discontinuities and for the velocity values are shown in their models, but the mean values were used in the gravity computation. It may be said that there is a fairly good agreement between the trend of computed gravities for both models and that of Bouguer anomalies.

In order to check the variation of theoretical gravity anomalies due to the change in a veleocity-density relation, the anomalies were computed as an example for Model II of the profile (8), using all of the four relations described in Section 2. The results are shown in Fig. 13, taking a reference level at the point where the Bouguer anomaly is zero.

It is to be noted that the maximum relative variation reaches 50 mgals. Except for the profiles (4) and (8), the theoretical anomalies from single-layer crustal models do not satisfy the observed gravity distribution, even if considerable allowance is made for various parameters including the choice of a standard section to be referred. On the other

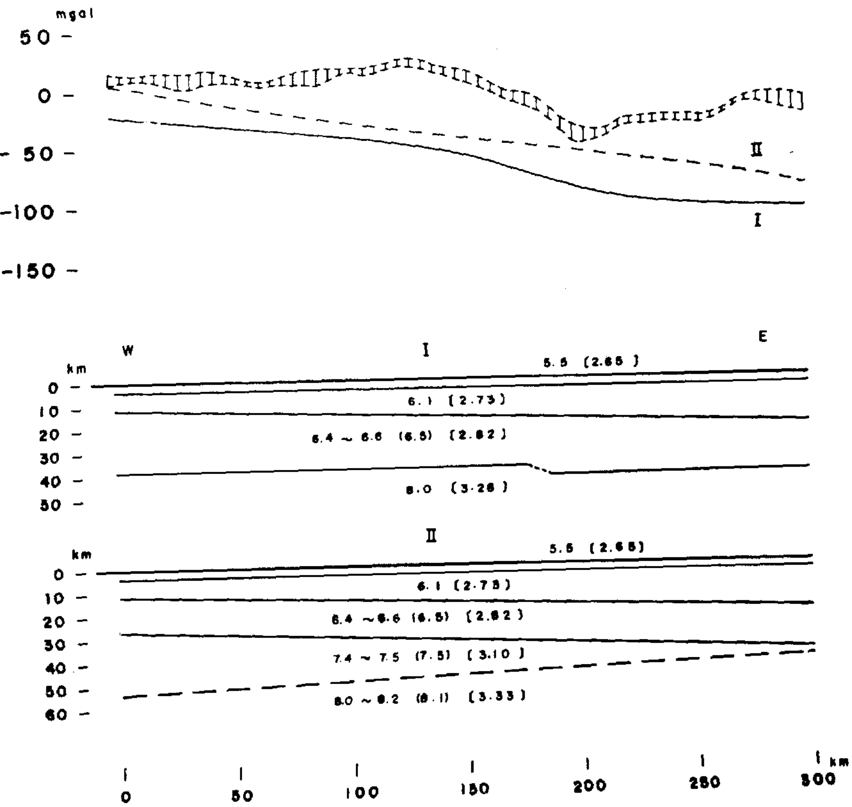


Fig. 12. Computed and Bouguer gravity anomalies, and the presented crustal model (after Hashizume *et al.*) along the Chubu-Kinki-Chugoku profile.

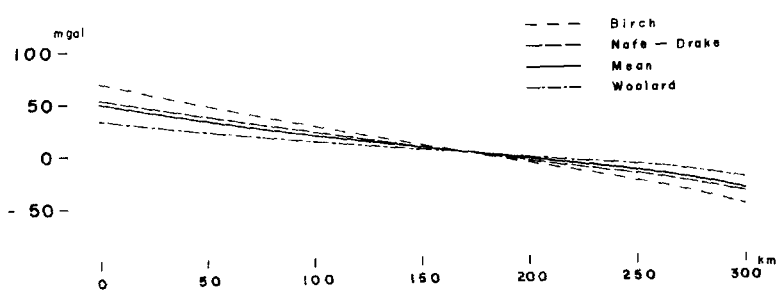


Fig. 13. Variation of theoretical gravity anomalies due to the change in velocity-density relations (for the Chubu-Kinki-Chugoku profile).

hand, a fairy good agreement is found for (4) and (8), both of which have common features with a lower crustal layer.

4. Modified Crustal Models and Gravity Anomalies

It has been shown that the crustal models with a single layer are not consistent with the distribution of Bouguer anomalies. In this section, a re-intepretation is made to travel time data in all profiles, on the assumption that there may be two or three crustal layers overlying the mantle. If recording stations were not spaced very closely, there remains some arbitrariness in drawing time distance curves, even under the assumption, and this would yield a different model. A number of possible solutions have been tested for each profile, incorporating distinct later phases to first arrivals. The gravity anomalies were also computed for all possible models, referring to a standard level common to all the profiles considered. In the following, some representative models derived from two or three different standpoints are described.

1. Western Japan

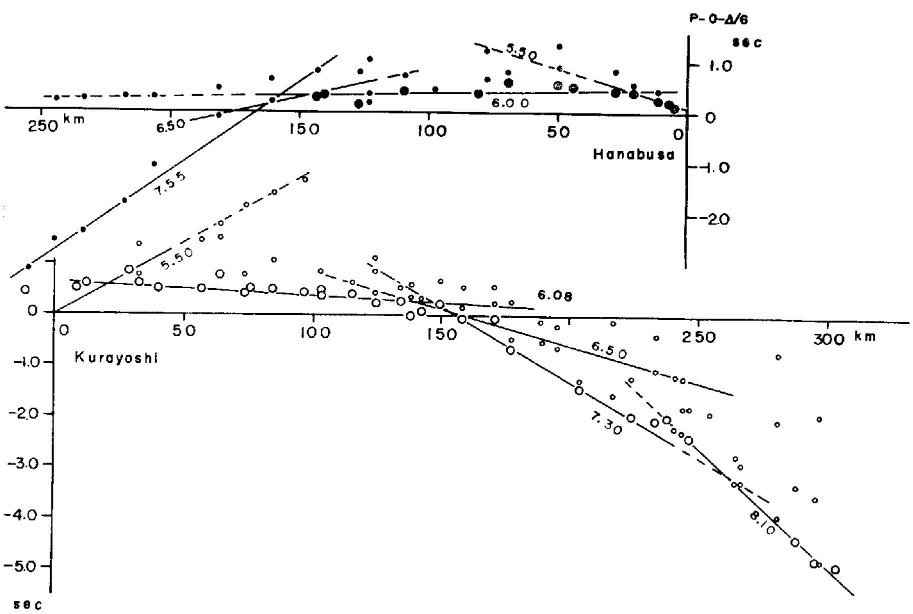


Fig. 14. Time-distance curves for the Chubu-Kinki-Chugoku profile.

In western Japan, seismic observations have been made along three profiles; Kinki A and B, and Kurayoshi-Hanabusa. The true velocity in the mantle is not yet definitely determined, but an apparent velocity higher than 8.0 km/sec has been observed for Pn waves in the last profile. For this reason, the velocity in the upper mantle is tentatively taken to be 8.0 km/sec in later computations throughout the three profiles, although this will have to be slightly modified when more information is available.

(1) Chubu-Kinki-Chugoku

This profile has been best surveyed by the reversed observations of the Kurayoshi-Hanabusa explosions (R.G.E.S., 1966). The traval time data are given in Fig. 14, in which three or four kinds of arrivals may be identified. Two velocities indicating the upper and lower crustal layers are undoubtedly identified, but there could be two ways of drawing time-distance lines beyond a distance of 200 km in the K-explosion. The lines drawn in Fig. 14 show the time-distance relation given Table 1 (1), adopt-

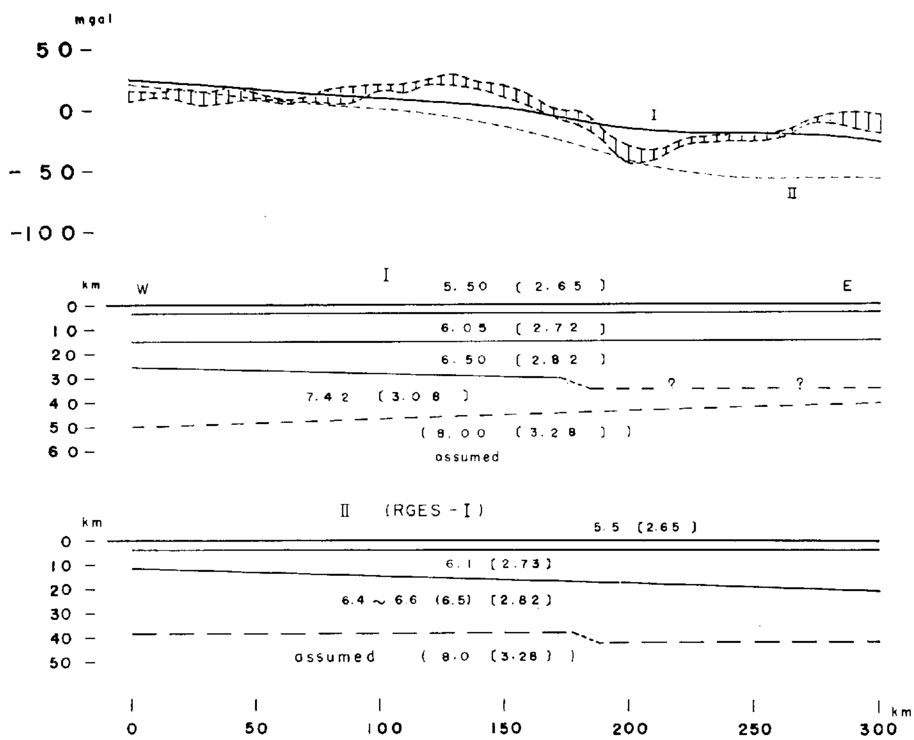


Fig. 15. Modified crustal models and gravity anomalies in the Chubu-Kinki-Chugoku profile.

ing a velocity corresponding to an intermediate layer. These yield a three-layer model with an overlying surface layer. There is a travel-time gap between T_4 and T_5 at a distance of about 240 km in the K-explosion, which would give a steep drop of the third discontinuity. Another standpoint is to associate the first arrivals observed beyond 200 km with Pn waves having an apparent velocity of about 8.0 km/sec. This leads to a double-layer model which was adopted as I by the R.G.E.S.. The derived models are specified in the table and are shown Fig. 15.

The computed and Bouguer gravity anomalies are compared in the upper part of the figure. Model I gives the gravity values in a close agreement with the distribution of observed anomalies, while the anomalies from Model II show some deviation toward east direction, although this could be reconciled by modifying crustal parameters.

(2) Kinki A

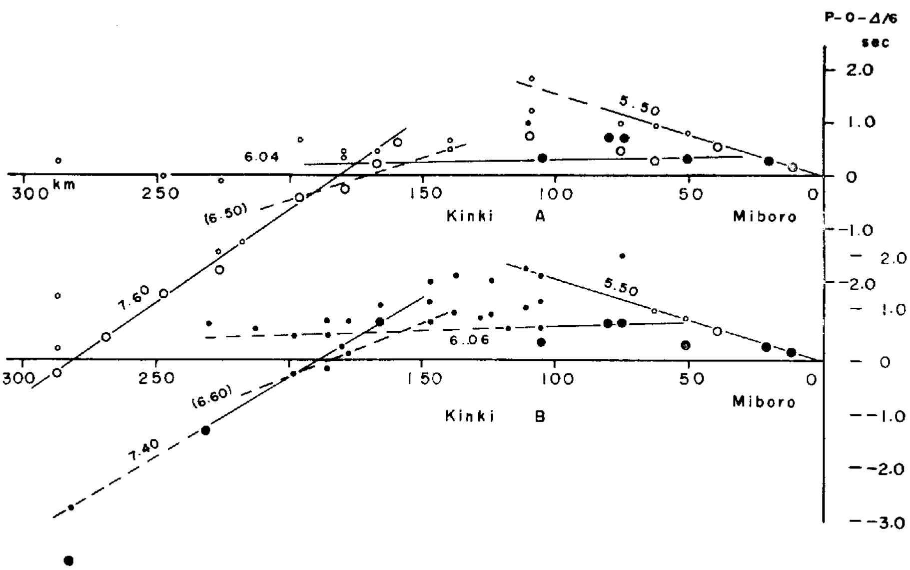


Fig. 16. Time-distance curves for the Kinki A and B profiles.

The time-distance curves may be drawn as shown in Fig. 16 for the data from the Miboro explosion. The third branch is rather hard to identify. It is to be noticed that the fourth branch with distinct arrivals is characterized by an apparent velocity of 7.60 km/sec which suggests the existence of an intermediate layer underlying the crust. A reversed

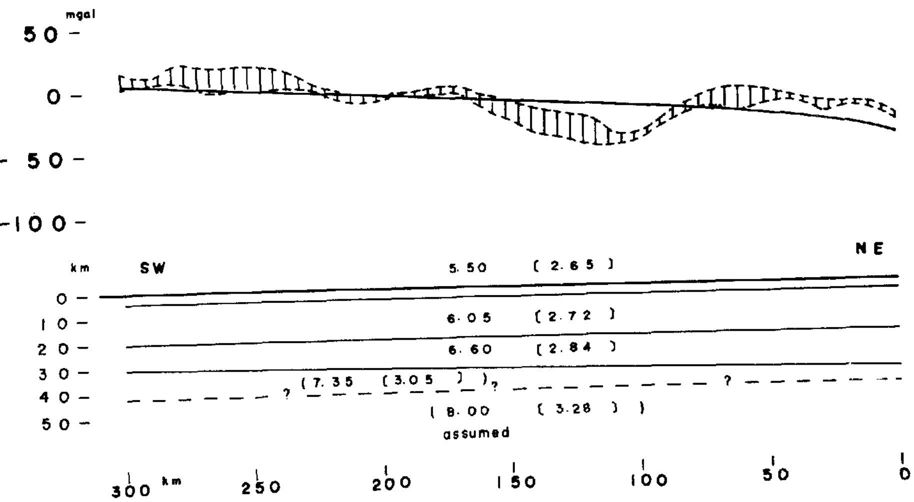


Fig. 17. A modified crustal model and gravity anomalies in the Kinki A profile.

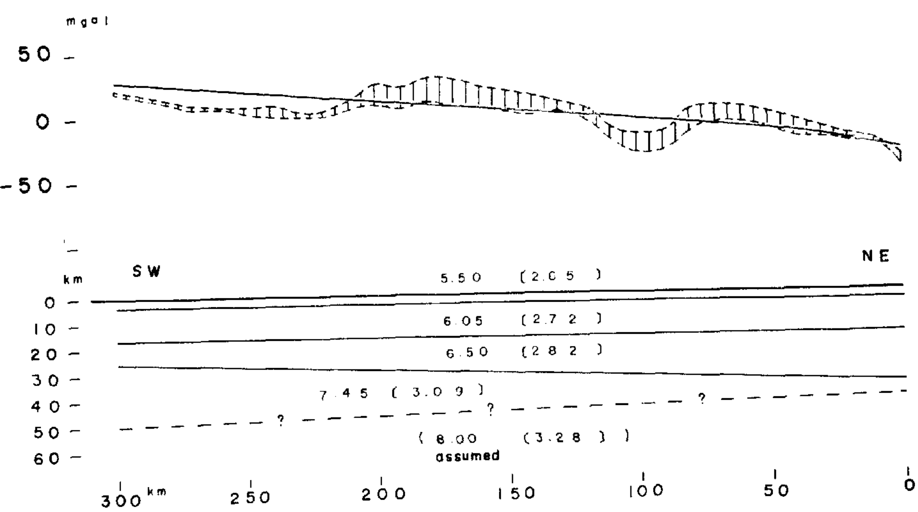


Fig. 18. A modified crustal model and gravity anomalies in the Kinki B profile.

measurement has not been made along this profile. If the apparent velocities from the Kurayoshi-explosion were combined to the present profile, such a model as shown in Fig. 17 would be obtained. The Moho-discontinuity was tentatively assumed to have the same depth as in the foregoing section, since there was no evidence for Pn waves from the Miboro explosion. Fig. 17 also shows a comparison between the computed and observed gravity anomalies, which may be regarded as agreeing well.

(3) Kinki B

Although the observed data for this profile are not good enough to allow us a precise velocity determination, the time-distance relation may be roughly estimated if data for the Kinki A profile are taken into account. The travel times would give a crustal model as illustrated in Fig. 18, if the apparent velocities of the Kurayoshi explosion were used together. There is an indication of seismic arrivals from the upper mantle at a most distant station, but the fourth boundary surface was tentativery given to be consistent with the Bouguer distribution. It is expected that more detailed information will be derived from reversed observations along this profile.

It appears that a synthetic treatment of travel-time data for the three profiles in western Japan and gravity anomalies favors a three-layer solution with the lower crust and an underlying intermediate layer. If the solution is adopted, the total thickness of the upper and lower crust is found to be about 37 km under Lake Biwa, and the depth to the undermost discontinuity may probably be in the order of 45 km around there.

2. Central Japan

Refraction measurements have been made along two main directions; one is the Chubu north-south and the other is the Chubu-Kwanto line. The latter has not been reversed. There is no definite evidence on the mantle velocity, but an apparent velocity of 7.7 km/sec or somewhat higher values has been observed. Several possible velocities are assumed in later computations for double-layered and three-layer models.

(1) Chubu N—S

A reversed profile has been completed along this line by the Shiunji, Annaka and Kawazu explsions and a Miyakejima earthquake. The time-distance diagram is shown in Fig. 19. An upper crustal velocity is found from all events, and apparent velocities of 6.7—6.9 km/sec belonging to the lower crust can be clearly identified. A higher velocity of 7.3 km/sec might be picked up from weak arrivals in the S- and K-explosions.

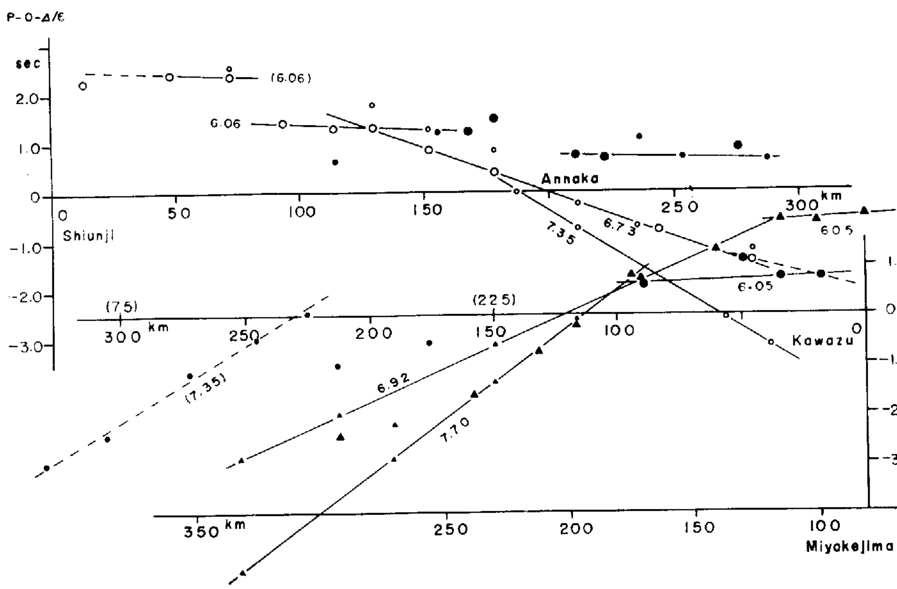


Fig. 19. Time-distance curves for the Chubu N-S profile.

i) If the mantle velocity is taken as 8.0 km/sec, the time-distance relation yields a three-layer model, Model I shown in Fig. 20. The fourth discontinuity in the range between 170 and 375 km was determined from the time-difference between T_3 and T_5 for the M-earthquake, and that for $\varDelta<150$ km was arbitrarily assumed to satisfy gravity data. ii) If an apparent velocity of 7.3 km/sec is not adopted because of rather weak arrivals, we have two-layer models named Model II. The cases A and B correspond to the assumed mantle velocity of 8.0 and 7.8 km/sec respectively. Time-distance relations and the crustal parameters for these models are given in Table 1 (4).

The computed gravity anomalies from the three types of models are shown in Fig. 20 together with Bouguer anomalies. The anomalies from Model I agree fairy well with the latter. There are large discrepancies up to 80—160 mgals in both cases of Model II, if the anomalies are referred to the same level as used for western Japan. This situation supports a three-layer solution, suggesting that there may be a thick intermediate layer underlying the crust in this profile.

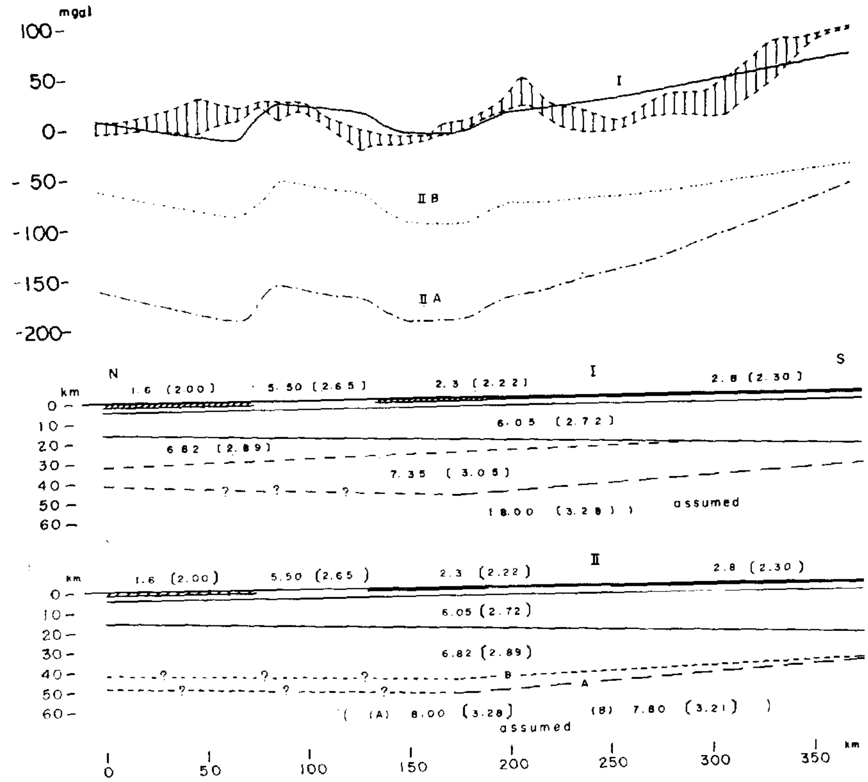


Fig. 20. Modified crustal models and gravity anomalies in the Chubu-N-S profile.

(2) Chubu-Kwanto

The Miboro explosion provided travel-time information to this profile, but the observation with rather widely spaced stations makes it difficult to identify the type of wave arrivals. Tentative time-distance lines are drawn in Fig. 21. Since a reversed measurement has not been made along this profile, the true velocities in crustal layers are not exactly known. i) If we assign velocities of 6.0, 6.8 and 7.4 km/sec to three layers, taking the results for the Chubu N—S section into account, and if the mantle velocity is assumed to be 8.0 km/sec, such a three-layer model shown as Model I in Fig. 22 is obtained. The depths to the third and fourth boundaries at the west end of this profile were determined from the results for the Chubu-Kinki-Chugoku section. ii) If we do not adopt the T_4-branch, two-layered models, Model II-A and II-B are obtained,

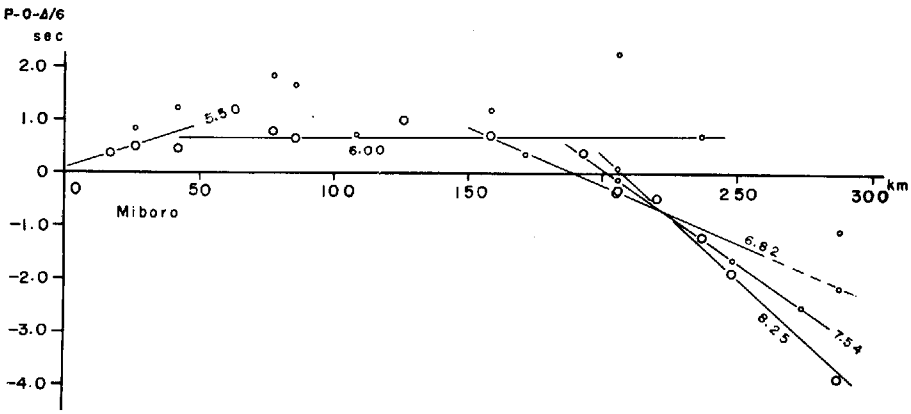


Fig. 21. Time-distance curves for the Chubu-Kwanto profile.

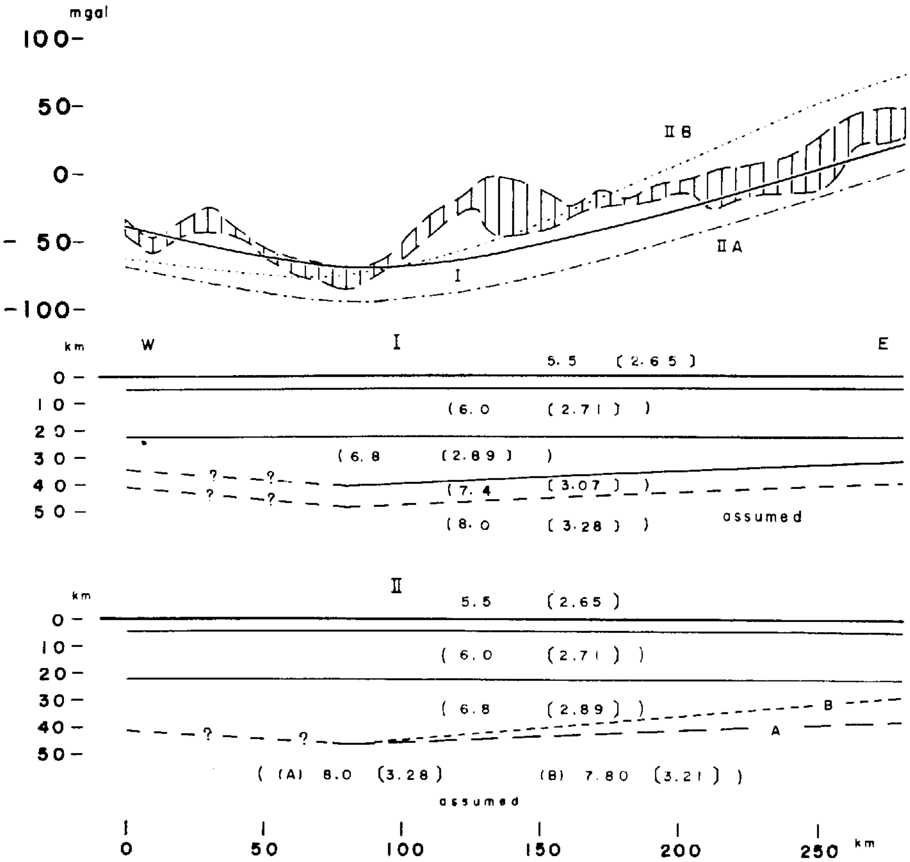


Fig. 22. Modified crustal models and gravity anomalies in the Chubu-Kwanto profile.

depending on the assumed mantle velocities of 8.0 and 7.8 km/sec. There is a good agreement between the trends of anomalies from Model I or II-A and of Bouguer anomalies, while Model II-B having a mantle velocity of 7.8 km/sec is not supported by the observed anomalies.

For the two profiles in central Japan, double-layered and three-layer models with variously assumed mantle velocities have been proposed. Comparison of the theoretical values with Bouguer anomalies seems to give support to a three-layer solution with a mantle velocity closer to 8.0 km/sec. It is reasonable to suppose that the lower crust or intermediate layer may be thick in this region including high mountain areas. The depth to the lowest boundary could reach more than 55 km.

3. Eastern Japan

Travel-time information has been obtained from seismic observations along two sections; Kwanto-Tohoku and Kwanto traversed in the SE–NW direction. A reliable value of the mantle velocity has not been determined, but it is possible to see a velocity of about 8.0 km/sec on the former profile, if weak arrivals are adopted. It is also reported (Ludwig *et al.*, 1966) that recent offshore seismic prospectings gave a mantle velocity of 8.0–8.3 km/sec off Sanriku coast in the north-eastern Japan trench. The velocity is assumed to take a value between 8.0 and 7.7 km/sec in later computations.

(1) Kwanto-Tohoku

The Hokoda II and Kamaishi explosions constitute a reversed profile along this line. Travel-time data are given in Fig. 23. The velocities for the upper and lower crust are well identified, and a line showing an apparent mantle velocity can be drawn for the H-explosion. Later arrivals with an apparent velocity of about 7.4 km/sec may be picked up. i) If we adopt a weak arrival from the K-explosion at a most distant station, the apparent velocity of the arrivals comes out to be 8.09, which gives a substantial mantle velocity of 8.0 km/sec by combing the corresponding velocity for the H-explosion. A three-layer model is obtained as shown in Fig. 24. ii) If arrivals having a velocity of 7.4 km/sec are neglected, we have a double-layered crust as indicated by Model II-A. In this case, however, another model designated as II-B is obtained, if 7.8 km/sec is used for the mantle velocity instead of 8.0. Time-distance relations and the determined parameters are specified in Table 1 (6). The computed gravity anomalies from Model II-B show a reverse trend against Bouguer

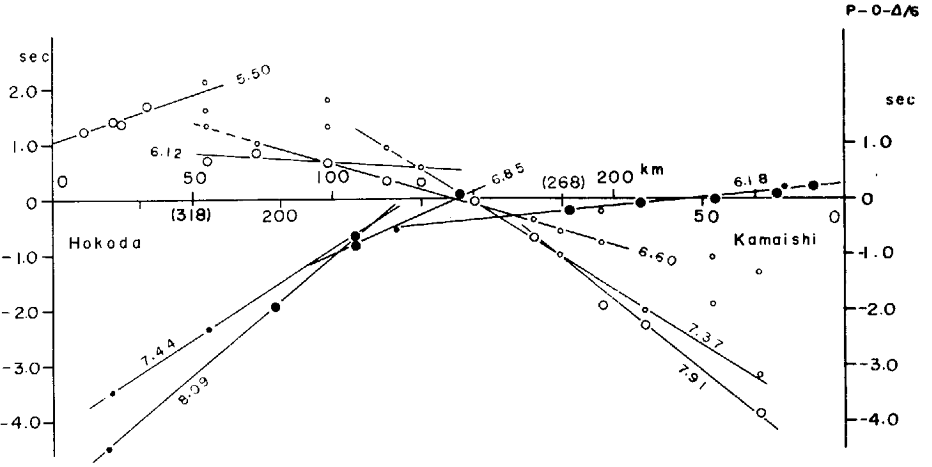


Fig. 23. Time-distance curves for the Kwanto-Tohoku profile.

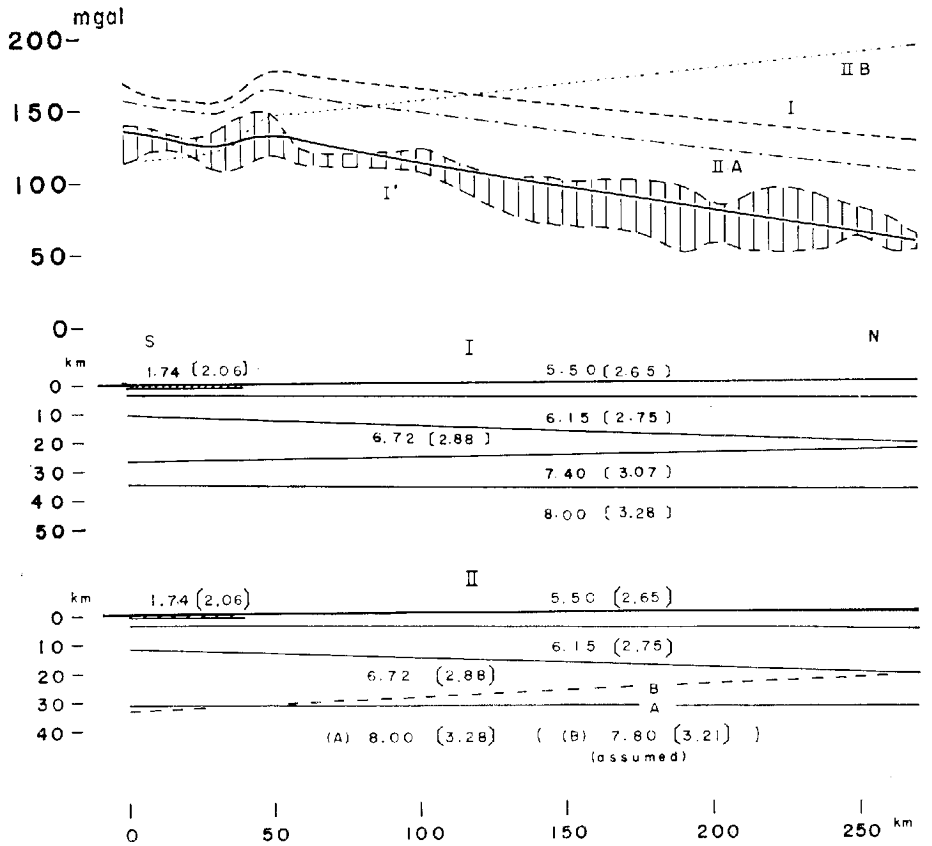


Fig. 24. Modified crustal models and gravity anomalies in the Kwanto-Tohoku profile.

anomalies. On the other hand, theoretical gravities from Models I and II-A run parallel with the Bouguer distribution with a difierence of 30 to 50 mgals. This fact suggests that the velocity in the upper mantle may be closer to 8.0 km/sec rather that to 7.8. It is not possible to say, at this stage, however, which of I and II-A would be suitable to the present profile.

(2) Kwanto

This profile has been covered by the reversed measurements of the Nozori and Hokoda I explosions. Travel times are shown in Fig. 25, in

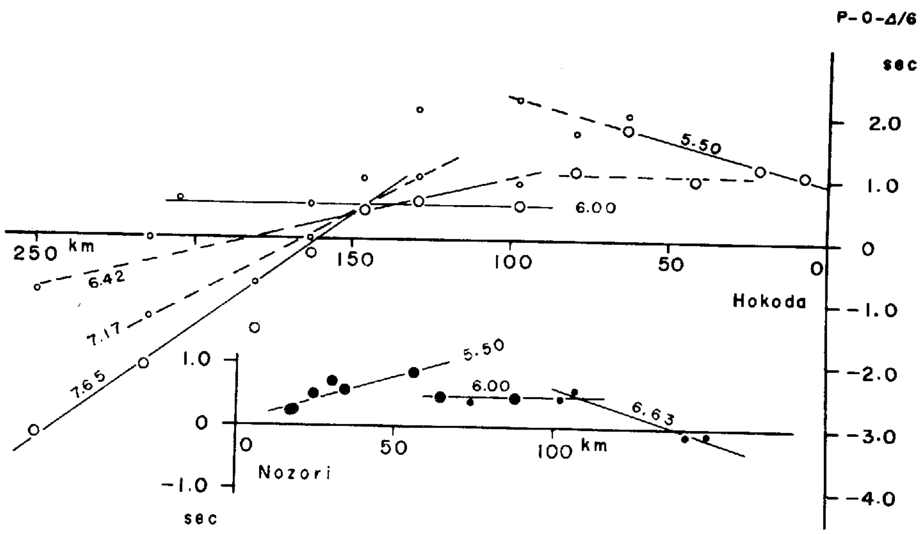


Fig. 25. Time-distance curves for the Kwanto profile.

which some scattering of data is seen at short distances. It is rather difficult to identify velocities belonging to the lower crust and intermediate layer, owing to the lack of data. i) If the velocities in the intermediate layer and the upper mantle are taken from the Kwanto-Tohoku profile, a three-layer model comes out to be as shown in Fig. 26. ii) On the assumption that the intermediate layer does not exist here, the observed travel-times give double-layered crusts, Model II-A and II-B, according to the assumed mantle velocity. Theoretical gravity anomalies expected from

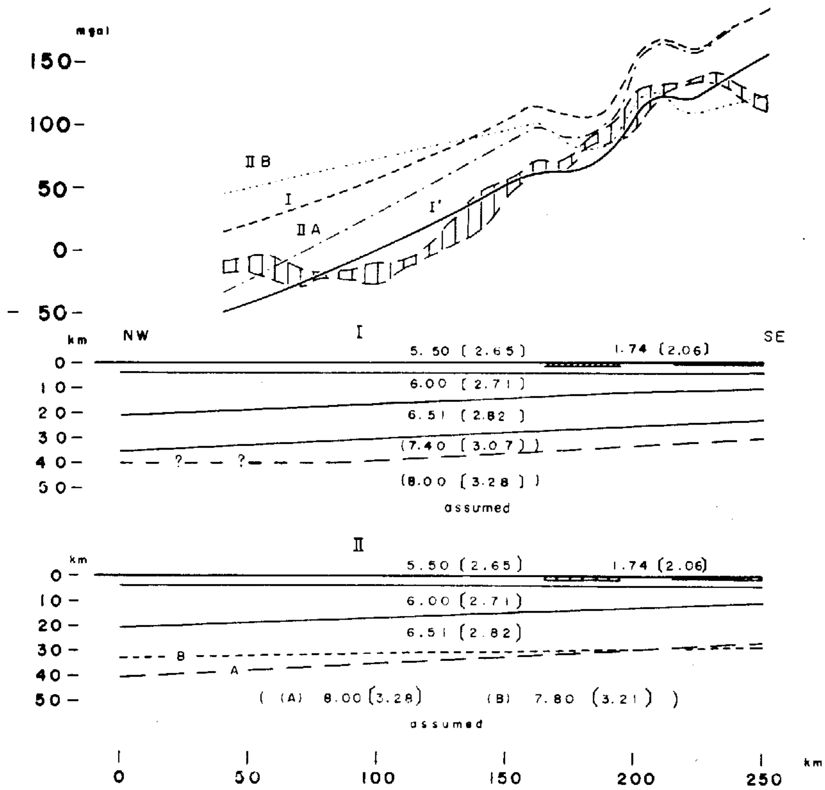


Fig. 26. Modified crustal models and gravity anomalies in the Kwanto profile.

the three models are compared in Fig. 26 with the Bouguer distribution. It can be seen that the computed values from Model II-B and the Bouguer trend make a remarkable discrepancy which would not be improved by the modification of crustal parameters. We can see a parallel trend in the cases of Model I and II-A. This implies that the mantle velocity has to be larger than 7.8 km/sec and that the latter two models cannot be discriminated solely by gravity data.

It appears that comparison between theoretical and observed gravities give support to a high mantle velocity being closer to 8.0 than to 7.8 km/sec also in the eastern region of Japan. There remains, however, a constant discrepancy up to about 40 mgals between the two kinds of anomalies in both models, if the computed values are referred to the same level as used for western and central Japan. This situation would arouse some interest about the structure in eastern Japan. A possible explanation is that the discrepancy would come from the difference in densities of crustal layers. To explain the disagreement of 40 mgals, the average crustal density would have to be smaller by 0.03 g/cm^3 or 1% in eastern Japan. The discrepancy could also be reconciled by reducing densities in the surface layer and the upper crust by 5.5 and 2% respectively, following a linear relation (M′) rather than the mean curve (M) between compressional velocity and density (See Fig. 2). Another possibility that the density in the upper mantle differs for the same velocity from the other regions cannot be ruled out, but it is impossible to make further inferences, unless a depth of compensation is known exactly.

5. Dispersion of Rayleigh Waves

Surface wave dispersion is controlled primarily by the distribution of shear wave velocities within the crust and mantle, while the gravity anomalies are sensitive to density contrasts between crustal layers and the upper mantle. The information from the dispersion of surface waves travelling across the regions now investigated may therefore be expected to provide another test to the appropriateness of the modified models.

The phase velocity of Rayleigh waves from distant earthquakes has been used by Aki and Kaminuma (Aki, 1961; Kaminuma and Aki, 1963; Kaminuma, 1964) to determine the crustal structure in various parts of Japan. They have compared the phase velocity data obtained from the seismological network of the Japan Meteorological Agency with theoretical dispersion curves based on a standard structure, which is somewhat different from the refraction results in Japan. Kanamori (1963) presented more realistic crust-mantle models being consistent with gravity and refraction data in a certain region. Recently, Kaminuma (1966) gave a similar model for central Japan, assuming a rather low mantle velocity of 7.7 km/sec, for which the phase velocities were computed and compared with his observed results. It is interesting, therefore, to compare theoretical dispersion expected from our results with their computed curve and with the observations of Aki and Kaminuma.

Theoretical phase velocity curves are first computed on the basis of the modified crustal models presented in the foregoing section. Some of the single-layer models, which have been presented by the R.G.E.S., are also taken into the computation to compare with two- or three-layered crust. The profiles now investigated may be divided into two or three sections, each being assumed to consist of horizontal parallel layers, for which theoretical dispersion can be computed. Densities in the layers are again assigned as given in the gravity calculation, and the shear velocities are estimated from the corresponding compressional velocities, assuming Poisson's ratio to be from 0.25 to 0.29. The computation has been made on an IBM 7090 computer from a program developed by Takeuchi, Saito and Kobayashi (1961). The observed phase velocities given by Aki and Kaminuma scatter in a rather wide range with comparatively large probable errors. No smoothing techniques, however, have been applied here to the observed velocity-period relation over some earthquakes, since it is natural to suppose that the scattering may be due to the incidence of waves from different directions into abruptly varied structures. For reference sake, the average velocities over all regions of Japan, which were given by the above authors, are plotted as small solid circles in the following figures.

1. Western Japan

Theoretical computations have been made for 7 horizontally-layered structures including 3 models with three layers, 2 double-layer models and one single-layer model, which were taken from the Chubu-Kinki-Chugoku and Kinki A profiles. The parameters specifying the structures are given in Table 2. Poisson's ratio was tentatively assumed as 0.27 in all layers. The computed phase velocity curves are shown in Figs. 27 (a) and (b) in comparison with observed velocities. It can be seen that the theoretical curve W-4A-1 seems to be consistent with the observations, while W-3A-1 and W-3A-2 or W-2B shows a significant deviation from them. Kanamori's curve for J-VI-1 (Hc=35 km) gives the best fit. If a Poisson's ratio of 0.25 was adopted for the upper crust, instead of 0.27, the computed curves displace by about 0.04 km/sec to higher velocities. This would not be enough to reconcile the deviation for the latter three cases, whereas W-4A-1 or 4A-2 would show a better agreement. This situation favors a three-layer solution over double- or single-layer models, indicating that there exists a rather thick intermediate layer with a velocity of about 7.4 km/sec in this region. The conclusion supports the inferences from the re-interpretation of refraction results and gravity anomalies.

2. Central Japan

The phase velocity curves have been computed for 15 models that

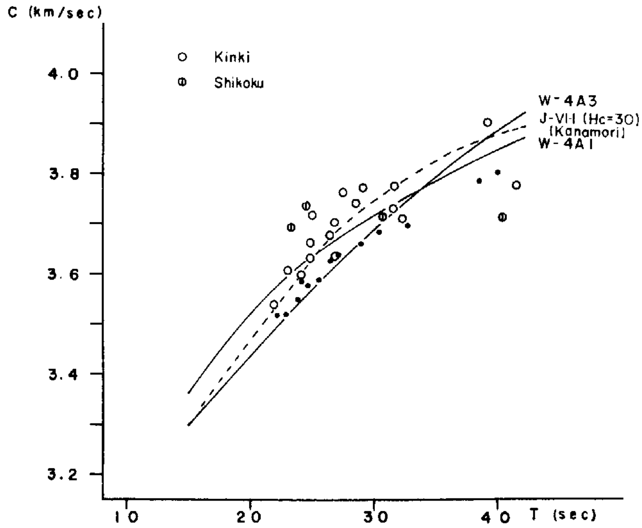
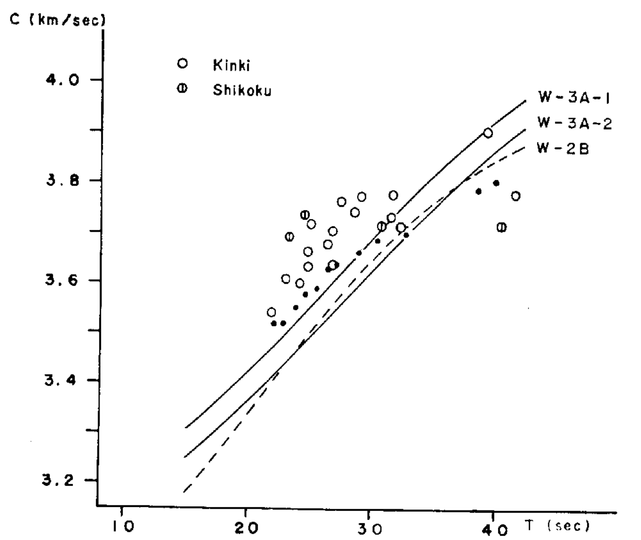


Fig. 27. Theoretical and observed phase velocities of Rayleigh waves in western Japan. (a) three-layer models



(b) double-layered models

were taken from the Chubu N–S and Chubu-Kwanto profiles. They include 6 three-layer models, 8 double-layer crusts and one single-layer model having variously assumed Poisson's ratios and mantle velocities. Their crustal parameters are tabulated in Table 3, in which a Poisson's ratio of 0.27 is assumed for 10 of the models. Fig. 28 (a) shows the theoretical curves based on three-layered models. Most of the observed phase velocities fall between or around the four curves C–4A–1, –2, –3 and –4, but it appears that the mean values for periods longer than 35 sec may be slightly lower than the curves. If we assume the Poisson's ratio as increasing with depth from 0.26 at the surface layer to 0.28 in the mantle, the theoretical curve C–4A–1 should displace to C–4A–1′ and C–4A–4 to C–4A–4′. This improves the deviation at longer periods. As can be seen in Figs. 28 (b) and (c), on the other hand, families of phase velocity curves from double-layered models with an assumed mantle velocity of 8.0 or 7.8 km/sec do not cover the observations, indicating large negative deviations. Even if Poisson's ratio in the crust was taken to be 0.25 instead of 0.27, the large discrepancy could not be reconciled as shown by a slight variation to higher velocities from C–3A–2 to C–3A–2′ or from C–3B–2 to C–3B–2′. It is also shown that a single-layer crust C–2A cannot account for the observed values. One of Kaminuma's models designated as

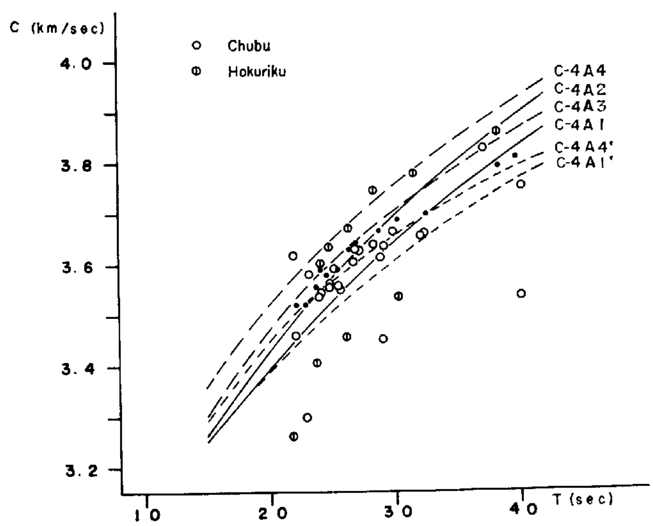
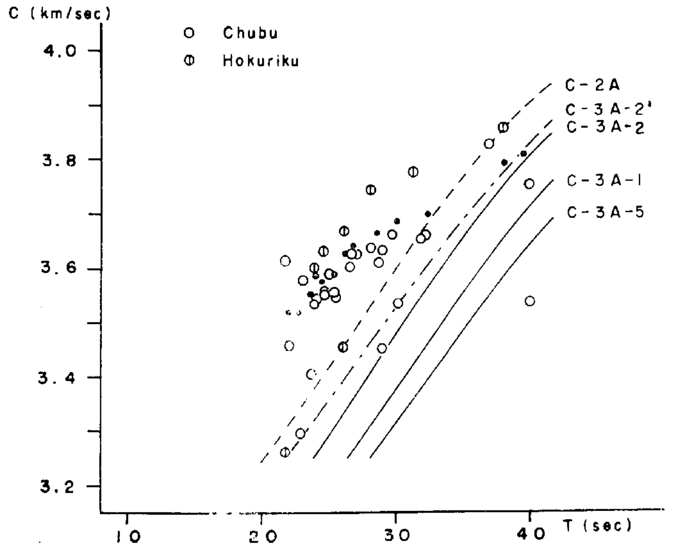
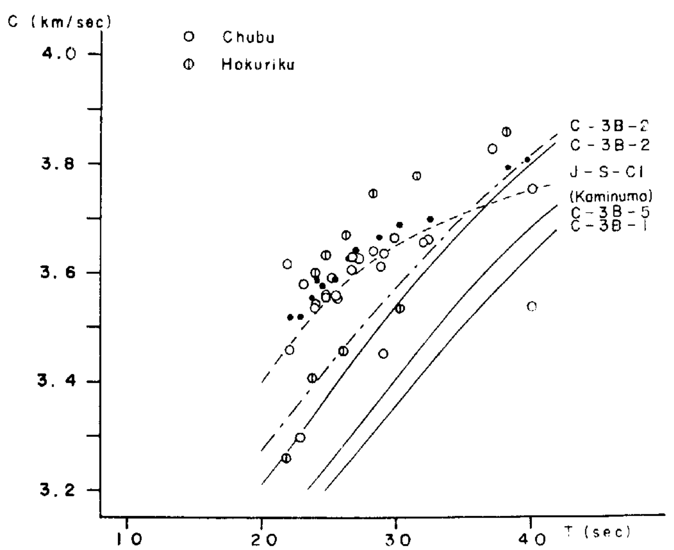


Fig. 28. Theoretical and observed phase velocities of Rayleigh waves in central Japan. (a) three-layer models



(b) double-layered models with a mantle velocity of 8.0 km/sec.



(c) double-layered models with a mantle velocity of 7.8 km/sec.

J–S–C1, having two crustal layers overlying the mantle with a low velocity of 7.7 km/sec, seems to agree well with the observations, but his model is not exactly based on refraction results. The above comparison of phase velocities gives support to the interpretation from the refraction and gravity data, that there must be a thick lower crustal and intermediate layers in this region.

3. Eastern Japan

The horizontally-layered models have been taken from 5 three-layer models, 6 double-layered crusts and one single layer model, which were presented for the Kwanto-Tohoku and Kwanto profiles. Their parameters are listed in Table 4. In Fig. 29 (a) are shown 3 theoretical curves computed from three-layer models having a Poisson's ratio of 0.27, indicating much higher values than observed velocities. To fit the observations, the ratio would have to take larger values. If it increases up to 0.29 in the mantle, the curves E–4A–2 and –3 go down to E–4A–2′ and –3′ respectively. A Poisson's ratio of 0.29 is not unlikely to occur, but this may be considered as a little larger value to be accepted for crustal rocks and mantle materials. On the other hand, the computed velocities from double-layered crustal models show good agreement with the observed values.

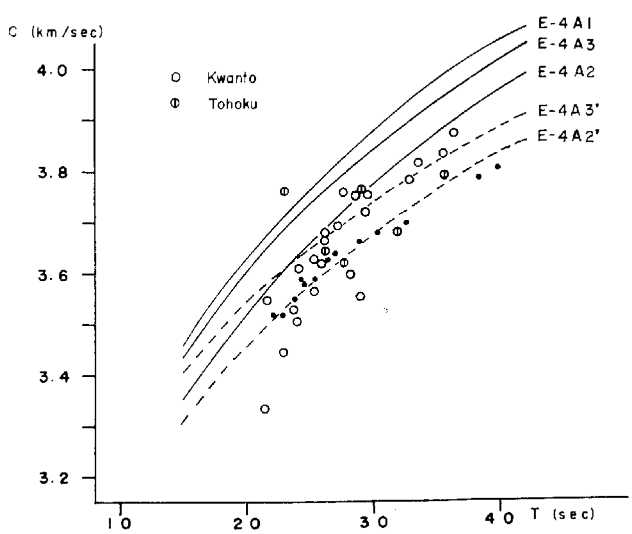
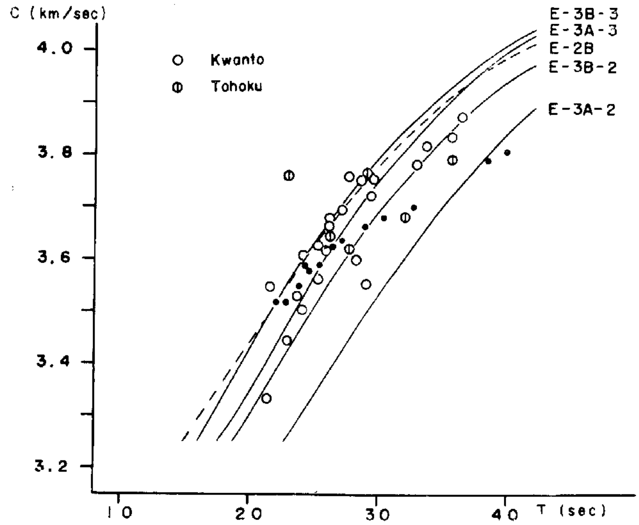


Fig. 29. Theoretical and observed phase velocity of Rayleigh waves in eastern Japan. (a) three-layer models



(b) double-layered models.

Most of the observed velocities fall between the curves E-3A-1 and -2, but E-3A-3 or E-3B-2 gives the best fit. This means that the mantle velocity in this region could be 7.8 km/sec solely in view of Rayleigh wave data, however, the interpretation encounters great difficulties with gravity anomalies. The conclusion is that the intermediate layer is unlikely to be here, but if it exists, it would be a thin layer with a high Poisson's ratio.

6. General Discussion and Concluding Remarks

The crustal structure along some profiles in Japan has been discussed on the basis of refraction results, gravity anomalies and the phase velocity of Rayleigh waves. The discussion has been confined two-dimensionally to 7 profiles in three regions, and cannot be extended without more information directly to whole regions traversed by the profiles. However, the conclusion obtained by the present analysis may still provide an aspect of the general features of the crustal structure.

The results show that crustal models with a single layer are not supported by gravity and surface wave data, even if allowance is made for the crustal parameters in computing theoretical values as well as for the observational errors. Alternative models with double- or three-layer crust, which were suggested by recent seismic observations and by Kanamori's work, have been presented for all the profiles through the re-interpretation of travel-time data. Theoretical gravity anomalies and phase velocity curves of Rayleigh waves have been computed from the modified crustal models and compared with their observations. The synthetic comparison favors a three-layer solution of modified models in western and central Japan, but two solutions are possible for eastern Japan. The main conclusions are summarized as follows. (1) The velocity in the upper mantle may be closer to 8.0 rather than to 7.7 km/sec which was proposed by the R.G.E.S. in their earlier work and has long been accepted. (2) It is reasonable to suppose that there may be a lower crustal layer with velocities of 6.5–6.8 km/sec and a thick intermediate layer having a velocity of about 7.4 km/sec, in western and central Japan. Poisson's ratio in the intermediate layer and the mantle might be large under the Chubu mountain region. (3) In eastern Japan, it is not certain whether there is a thin intermediate layer or not. If it exists, Poisson's ratio should have higher values in the lower crust and mantle. The average crustal density might be smaller by 1% than that in the other regions. (4) Velocities of 6.5–6.8 km/sec in the lower crust may be associated with basis rocks such as gabbro (Birch, 1961). The average depths to the base of the lower crust are estimated to be 32–35 km in the Tohoku, 27–31 km in the southeast Kwanto, 38–40 km in the northwest Kwanto regions in the double-layer models respectively, and 36–40 km in the Chubu, 28–30 km in the Kinki and 25–28 km in the Chugoku regions in the three-layer models respectively. The nature of the intermediate layer with a velocity of about 7.4 km/sec leaves some questions. It is supposed that the layer might be composed mainly of ultrabasic materials, for example, peridotite, but to infer the composition in more detail is beyond the scope of this paper. A question whether this layer should be included in the crust or the mantle is left unanswered. If there exists the layer, the depths to the lower boundary would be 35–38 km, 33–36 km, 35–40 km, 48–55 km, 42–48 km and 45–50 km at most for the said regions respectively. Some of the conclusions may probably be modified, when more information is available.

It should be noted here that the computed gravity anomalies have been referred to a standard crustal section which was chosen to fit the distribution of Bouguer anomalies in all the profiles investigated. This section is equivalent to a structure for which the Bouguer anomaly is zero. The average crustal density over the three regions is 2.87, if densities are assigned from the mean velocity — density curve. To give the zero anomaly with the average density and an assumed mantle density of 3.28, the average crustal thickness has to be 43.8 km including the intermediate layer. Although different crustal sections have been used as a reference in previous gravity studies in the United States, the computed anomalies from an arbitrary structure should be larger by 170 mgals, if they refer to our present section instead of the standard continent of Worzel and Shubert (1955). This is essentially the same thing with the fact (Aki, 1961) that for the same observed phase velocity of Rayleigh waves the observed Bouguer anomaly is larger by 160 mgals in Japan than in North America. The above consideration suggests a possibility that the density of the upper mantle in Japan could be smaller than that in the continent. An arbitrary assumption that $\rho_M=3.33$, $\rho_C=2.90$ (Steinhart and Meyer, 1961) and $Hs=39.7$ km would account for the discrepancy, if a depth of compensation is taken to be 57 km.

The observations of Love waves, when more data are accumulated, will be compared with theoretical velocities expected from the present results. To confirm the conclusion obtained in this study, further attempts will be made to infer the crust-mantle structure under specific regions by the use of Fourier spectrum of long-period body waves.

Note added in proof

1) The Research Group for Explosion Seismology recently (1966, Annual Meeting of Seism. Soc.) gave a crustal model for a profile across the Tohoku region from northwest to southeast, from the observations of the Kesennuma, Oga and Tsuchihata explosions. The model is a double layered crust with velocities of 6.1 and 6.9 km/sec and a thickness of 30–34 km overlying the mantle having a velocity of 8.0 km/sec.

2) Kurita (1966, Annual Meeting of Seism. Soc.) found from the spectral features of long period P waves from distant earthquakes that there seems to be two crustal layers and a thick intermediate layer under the Matsushiro area in central mountain region, and that the depth to the base could be more than 60 km.

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Table 1. Time-distance relations and computed crustal parameters.

(1) Chubu-Kinki-Chugoku

Kurayoshi

$T_2=\Delta/6.08+0.55$
$T_3=\Delta/6.50+1.92$
$T_4=\Delta/7.30+4.58$
$T_5=\Delta/8.10+8.17$

Hanabusa

$T_1=\Delta/5.50+0.19$
$T_2=\Delta/6.04+0.43$
$T_3=\Delta/6.50+2.28$
$T_4=\Delta/7.55+5.74$

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	Depths (km) $\Delta=300$	Dip
I, II	0	5.50	3.0	3.0	0°
	1	6.06	15.0	15.0	0°
I	2	6.50	25.3	34.6	1°47′
	3	7.42	50.0	41.1	−1°42′
	M	(8.00)			
II	2	6.50	38.5	41.0	0°
	M	(8.00)			

(2) Kinki A

Miboro

$T_1=\Delta/5.50$
$T_2=\Delta/6.04+0.35$
$T_3=\Delta/6.50+2.16$
$T_4=\Delta/7.60+0.36$

(3) Kinki B

Mobiro

$T_1=\Delta/5.50$
$T_2=\Delta/6.06+0.70$
$T_3=\Delta/6.60+2.68$
$T_4=\Delta/7.40+5.89$

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	Depths (km) $\Delta=300$	Dip
A	0	5.50	3.0	3.0	0°
	1	6.05	16.2	16.2	0°
	2	6.50	35.2	25.4	−2°03′
	3	7.45	(41.0)	(50.0)	(1°42′)
	M	(8.00)			
B	0	5.50	4.0	4.0	0°
	1	6.05	20.2	20.2	0°
	2	6.60	34.9	30.6	−0°49′
	3	7.35	(41.1)	(43.0)	
	M	(8.00)			

(4) Chubu N-S

Shiunji

$T_2 = \Delta/6.06 + 2.48$

$T_2' = \Delta/6.06 + 1.55$

$T_3 = \Delta/6.73 + 3.65$

$(T_4 = \Delta/7.35 + 5.73)$

Kawazu

$T_1 = \Delta/5.50 + 0.45$

$T_2 = \Delta/6.05 + 0.80$

$(T_4 = \Delta/7.35 + 6.68)$

Annaka

$T_2 = \Delta/6.05 + 1.32$ (N)

$T_2' = \Delta/6.05 + 0.73$ (S)

Miyakejima

$T_2 = \Delta/6.05 +$ 01h 06m 37.0s

$T_3 = \Delta/6.92 +$ 01h 06m 39.4s

$T_4 = \Delta/7.75 +$ 01h 06m 42.0s

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	$\Delta=175$	$\Delta=312$	$\Delta=375$	Dip
I, II	S	1.6—2.8	1.7	1.1	0.4	0.4	
	0	5.50	4.0	4.0	4.0	4.0	0°
	1	6.05	15.7	20.4	24.0	25.7	1°32′
I	2	6.82	31.7	28.6	24.0		—1°09′
	3	7.35	(41.0)	48.1	40.0	36.2	—3°24′
	M	(8.00)					
II-A	2	6.82	(48.7)	53.5		39.8	—3°55′
	M	(8.00)					
II-B	2	6.82	(42.1)	46.1		38.6	—2°10′
	M	(7.80)					

(5) Chubu-Kwanto

Miboro

$T_1 = \Delta/5.50 + 0.15$

$T_2 = \Delta/6.00 + 0.68$

$T_3 = \Delta/6.82 + 3.81$

$T_4 = \Delta/7.54 + 6.89$

$(T_5 = \Delta/8.25 + 9.48)$

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	$\Delta=80$	$\Delta=280$	Dip
I, II	0	(5.50)	4.7	4.7	4.7	0°
	1	(6.00)	22.3	22.3	22.3	0°
I	2	(6.82)	(33.0)	40.5	31.6	—2°34′
	3	(7.40)	(41.1)	48.6	39.7	—2°34′
	M	(8.00)				
II-A	2	(6.80)	(41.5)	46.6	37.2	—2°42′
	M	(8.00)				
II-B	2	(6.80)	(41.5)	46.5	28.5	—5°09′
	M	(7.80)				

(6) Kwanto-Tohoku

Hokoda	Kamaishi
$T_1=\Delta/5.50+1.01$	
$T_2=\Delta/6.12+0.94$	$T_2=\Delta/6.18+0.27$
$T_3=\Delta/6.60+2.18$	$T_3=\Delta/6.85+2.77$
$T_4=\Delta/7.37+4.59$	$T_4=\Delta/7.44+4.94$
$T_5=\Delta/7.91+6.23$	$T_5=\Delta/8.09+6.44$

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	$\Delta=250$	Dip
I, II	S	1.74	0.9		
	0	5.50	3.5	5.9	0°33′
	1	6.15	11.4	20.6	2°07′
I	2	6.72	26.6	23.8	−0°38′
	3	7.40	34.6	37.4	0°38′
	M	8.00			
II-A	2	6.72	31.7	32.5	0°10′
	M	8.00			
II-B	2	6.72	33.0	23.8	−2°07′
	M	(7.80)			

(7) Kwanto

Hokoda	Nozori
$T_1=\Delta/5.50+0.92$	$T_1=\Delta/5.50+0.10$
$T_2=\Delta/6.00+1.00$	$T_2=\Delta/6.00+0.55$
$T_3=\Delta/6.42+2.03$	$T_3=\Delta/6.63+2.23$
($T_4=\Delta/7.16+4.43$)	
$T_5=\Delta/7.65+5.76$	

Model	Layer	Velocity (km/sec)	Depths (km) $\Delta=0$	$\Delta=250$	Dip
I, II	S	1.74	0.8		
	0	5.50	4.0	4.0	0°
	1	6.00	10.7	20.7	2°18′
I	2	6.51	22.9	35.5	2°53′
	3	(7.40)	30.1	(40.0)	3°32′
	M	(8.00)			
II-A	2	6.51	26.5	40.8	3°16′
	M	(8.00)			
II-B	2	6.51	28.1	33.1	1°08′
	M	(7.80)			

Table 2. Parameters in horizontally-layered models for western Japan.

Layer	Hj			ρ	Vp	Vs	σ
	W-4A1	W-4A2	W-4A3				
0	3.0	3.0	3.0	2.65	5.50	3.10	0.27
1	12.6	12.6	12.6	2.72	6.05	3.40	0.27
2	11.3	14.6	19.0	2.82	6.50	3.65	0.27
3	21.6	15.3	7.9	3.08	7.40	4.15	0.27
M	∞	∞	∞	3.28	8.00	4.50	0.27
Layer	W-3A1	W-3A2					
0	3.7	3.7		2.65	5.50	3.10	0.27
1	9.6	15.2		2.73	6.10	3.43	0.27
2	25.0	22.6		2.82	6.50	3.65	0.27
M	∞	∞		3.28	8.00	4.50	0.27
	W-2B						
0	6.0			2.65	5.50	3.18	0.25
1	22.0			2.71	6.00	3.36	0.27
M	∞			3.12	7.50	4.21	0.27

* Hj is a layer thickness in km, Vp and Vs are compressional and shear velocities in km/sec and ρ is a density in g/cm^3.

** The above horizontal models were taken from the following sections of modified structures.

Model	Profile
W-4A1	W (1) 0-100 km; W (2) 200-300 km
W-4A2	W (1) 100-200 km; W (2) 100-200 km
W-4A3	W (1) 200-300 km; W (2) 0-100 km
W-3A1	W (1) 0-120 km
W-3A2	W (1) 180-300 km
W-2B	W (2) Model II of the RGES.

Table 3. Parameters in horizontally-layered models for central Japan.

Layer	Hj				ρ	Vp	Vs	σ	Vs′	σ′
	C-4A1,1′	C-4A2	C-4A3	C-4A4,4′						
0	4.7	4.7	4.0	4.0	2.65	5.50	3.10	0.27	3.13	0.2
1	17.6	17.6	13.7	17.6	2.72	6.05	3.40	0.27	3.40	0.2
2	17.1	12.7	13.0	7.1	2.89	6.80	3.82	0.27	3.82	0.2
3	7.6	7.5	10.3	17.3	3.05	7.35	4.12	0.27	4.05	0.2
M	∞	∞	∞	∞	3.28	8.00	4.50	0.27	4.40	0.2
	C-3A1	C-3A2,2′	C-3A5							
0	4.7	4.7	4.0		2.65	5.50	3.10	0.27	3.18	0.2
1	17.6	17.6	19.0		2.72	6.05	3.40	0.27	3.49	0.2
2	23.1	19.6	24.6		2.89	6.80	3.82	0.27	3.92	0.2
M	∞	∞	∞		3.28	8.00	4.50	0.27	4.50	0.2
	C-3B1	C-3B2,2′	C-3B5							
0	4.7	4.7	4.0		2.65	5.50	3.10	0.27	3.18	0.2
1	17.6	17.6	19.0		2.72	6.05	3.40	0.27	3.49	0.2
2	22.0	15.2	19.3		2.89	6.80	3.82	0.27	3.92	0.2
M	∞	∞	∞		3.21	7.80	4.37	0.27	4.37	0.2
	C-2A									
0	5.0				2.65	5.50	3.18	0.25		
1	30.6				2.71	6.00	3.36	0.27		
M	∞				3.24	7.90	4.43	0.27		

* Hj is a layer thickness in km, Vp and Vs are compressional and shear velocities km/sec and ρ is a density in g/cm³.

** The above horizontally-layered models were taken from the following sections modified structures.

Model	Profile
C-4A1, 4A1′, 3A1, 3B1	C (2) 30–130 km
C-4A2, 3A2, 3A2′, 3B2, 3B2′	C (2) 130–230 km
C-4A3	C (1) 0–100 km
C-4A4, 4A4′	C (1) 100–200 km
C-3A5, 3B5	C (1) 175–375 km
C-2A	C (2) 0–250 km (Model II of the RGES)

Table 4. Parameters in horizontally-layered models for eastern Japan.

Layer	Hj		ρ	Vp	Vs	σ	Vs'	ρ'
	E-4A1	E-4A2, 2'						
0	4.0	4.0	2.50	5.50	3.10	0.27	3.13	0.26
1	8.8	12.8	2.66	6.05	3.40	0.27	3.45	0.27
2	12.8	13.8	2.84	6.60	3.70	0.27	3.65	0.28
3	7.9	8.9	3.08	7.40	4.15	0.27	4.05	0.285
M	∞	∞	3.28	8.00	4.50	0.27	4.35	0.29
	E-4A3, 3'	E-3A3						
0	4.5	4.5	2.50	5.50	3.10	0.27	3.13	0.26
1	10.6	10.6	2.70	6.15	3.40	0.28	3.45	0.27
2	10.5	16.9	2.88	6.70	3.70	0.28	3.70	0.28
3	10.3	0.0	3.08	7.40	4.15	0.27	4.05	0.285
M	∞	∞	3.28	8.00	4.50	0.27	4.35	0.29
	E-3A1	E-3A2						
0	4.0	4.0	2.50	5.50	3.10	0.27		
1	8.8	12.8	2.66	6.05	3.40	0.27		
2	16.6	21.1	2.84	6.60	3.65	0.27		
M	∞	∞	3.28	8.00	4.50	0.27		
	E-3B1	E-3B2						
0	4.0	4.0	2.50	5.50	3.10	0.27		
1	8.8	12.8	2.66	6.05	3.40	0.27		
2	16.3	15.3	2.84	6.60	3.65	0.27		
M	∞	∞	3.21	7.80	4.37	0.27		
	E-3B3							
0	4.5		2.50	5.50	3.10	0.27		
1	10.6		2.70	6.15	3.40	0.27		
2	14.2		2.88	6.70	3.65	0.27		
M	∞		3.21	7.80	4.37	0.27		
	E-2B							
0	6.0		2.65	5.50	3.18	0.25		
1	21.0		2.73	6.10	3.42	0.27		
M	∞		3.18	7.70	4.32	0.27		

* Hj is a layer thickness in km, Vp and Vs are compressional and shear velocities in km/sec, and ρ is a density in g/cm.^{3}

** The above horizontally-layered models were taken from the following sections of modified structures.

Model	Profile
E-4A1, 3A1, 3B1	E (2) 0–100 km
E-4A2, 4A2', 3A2, 3B2	E (2) 100–200 km
E-4A3, 4A3', 3A3, 3B3	E (1) 50–150 km
E-2B	E (2) 0–200 km (Model I of the RGES)

50. 日本の地殻構造についての一考察

——爆破・重力・表面波資料による——

京都大学防災研究所　三　雲　　健

日本の地殻構造については，すでに爆破地震動や表面波の観測，重力異常の解析などによって多くの研究が行われているが，これら3種の情報を組合わせれば，いくつかの可能なモデルの取捨選択に役立つことが期待される．このような方法は日本では金森がすでに試みているが，こゝでは今迄に行われた爆破地震動の走時にもとづき，種々の可能なモデルを推定し，これらのモデルから期待される重力異常と Rayleigh 波位相速度の理論値を計算してそれぞれの観測値と比較する方法を採った．重力異常の計算には，地震波速度と岩石密度との関係，比較の標準としてとるべき構造などの仮定が含まれるために，その絶対値を論ずることは難しいが，相対的な変化を Bouguer anomaly の傾向と比べることが出来る．一方，表面波位相速度は S 波の速度分布につよく支配されるために Poisson ratio がとり得る値を検討しなければならない．これらの問題を考慮に入れて，地殻構造の考察を行なった結果は次の通りである．

先に爆破観測から出されたモデルのうち，single layer の構造は，重力および Rayleigh 波位相速度の何れにもあまりよく合わないようである．このため，最近の観測結果を考慮して各測線の走時データを再検討し，地殻下部層あるいは中間層を含むような2層構造または3層構造を考え，これらについて重力異常と，表面波位相速度を計算した．この両者をそれぞれの観測値と比べると，マントル上部の速度は従来考えられていた 7.7 よりはむしろ 8.0 km/sec に近いと考えた方が良さそうである．西日本および中部日本においては，6.5—6.8 km/sec の速度を持つ地殻下層とマントルの間にはかなり厚い中間層（速度 7.4 程度）をおく方が観測結果をよく説明する．中部日本ではこの中間層と上部マントルでは S 波速度が普通よりやゝおそいと思われる．これに反して，東日本においては，中間層が存在するかどうかは確かでない．若し存在するとしても，西部，中部にくらべてはるかに薄いものと思われ，この場合は，S 波速度がやはりおそいと考えなければならない．また重力異常の比較の結果，東日本の地殻の平均密度は他の地方に比べて 1% 程度小さいと考えなければならないが，これは速度密度の関係が，この地方に対してだけ異るためかも知れない．

求められたモデルにおける第2層（地殻下部層）底部迄の平均の深さは，2層モデルでは東北 32-35 km，関東南東部 27-31 km，関東北西部 38-40 km，3層モデルでは中部 36-40 km，近畿 28-30 km，中国 25-28 km である．この下にある中間層の厚さについては確かではないが，西日本で 15-20 km，中部日本でも同程度，東日本ではもしあるとしても 10 km 以下と思われる．

なお，日本の平均的構造を北アメリカの場合と比べると，同じような構造に対しては，日本の方の重力異常がはるかに大きい，このことは上部マントルの密度の差に原因があるのかも知れない．